THE DESIGN ASPECTS OF A LOW TEMPERATURE HIGH PRESSURE PLASMA WIND TUNNEL

by

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B. S., Kansas State University, 1961

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
MANHATTAN, KANSAS

1962

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NOMENCLATURE

$B(t)$	Collision term in Boltzmann's equation
$\bar{B}$	Magnetic field intensity, gauss
$\bar{F}$	Body force
$f(\bar{r},\bar{w})$	Particle distribution function
$\bar{g}$	Particle flux in velocity space
$\bar{J}$	Electric field strength, ampere-meter
m	Electron mass
M	Mass of gas atom
n	Electron density
P_e	Pressure excess
P_m	Probability of collisions which result in momentum transfer
P_x	Probability of collisions which result in excitation
P_i	Probability of collisions which result in ionization
P_L	Legendre polynomial
q	Recombination frequency
t	Time
u	Component of velocity in x direction
v	Component of velocity in y direction
w	Component of velocity in z direction
ω	Frequency, radians per second
v_e	Electron velocity
$\bar{W}$	Total velocity with components u, v, w
$\bar{\gamma}$	Particle flux in coordinate space
ν_m	Frequency of collisions resulting in momentum exchange
ν_x	Frequency of collisions resulting in excitation

ν_i	Frequency of collisions resulting in ionization
μ	Dynamic viscosity
ρ	Mass density
λ	Mean free path
$\bar{\nabla}$	Gradient operator in rectangular coordinates
$\bar{\nabla}_r$	Gradient operator in polar coordinates
$\bar{\nabla}_v$	Gradient operator in velocity coordinates
—	Vector quantities are denoted by a bar such as $\bar{B}$, $\bar{W}$, etc.
ρ_o	Mass density of gas at standard conditions
$\mathcal{W}$	Weight of vane
g	32.2 ft/sec^2
C_D	Drag coefficient of vane
A	Area of vane
T	Gas temperature
p	Gas pressure
θ	Angle of vane deflection
$\bar{r}$	Position vector
j	$\sqrt{-1}$
e	Charge on an electron
$\bar{E}$	Potential gradient

INTRODUCTION

Recently, much attention has been given to the study of high temperature plasma. That is, thermally ionized gases in the 10,000 to 15,000 degree Fahrenheit range. The projected uses of high temperature plasma, which include materials testing and power generation, are well known. However, there are some considerations due ionized gases which can not be easily investigated with present plasma facilities because of the physical problems associated with this area of high temperature. For example, little is presently known about heat transfer through ionized gases, plasma boundary layers, and the general aspects of plasma dynamics other than at very low pressures or at very high temperatures. So, the amount of useful knowledge derivable from a low temperature, moderate pressure plasma facility is presently quite large. Here low temperature corresponds to a macroscopic plasma temperature of 60 degrees Fahrenheit to 80 degrees Fahrenheit and a moderate pressure is taken as 1 to 10 mm of mercury absolute. The design and construction of a low temperature plasma facility involves two major problems: plasma generation and flow production. This thesis will investigate these two problems analytically and show that the experimental evidence tends to substantiate the analyses.

PLASMA GENERATION

Fundamentally, the theoretical problem of gas breakdown or ionization is a simple one. An outer orbit electron will leave the bonds of an atom if it is given a sufficient amount of energy. Practically speaking, the process of supplying that electron with sufficient energy is a difficult

one to make even moderately efficient. If given enough thermal energy, a gas will be ionized as a result of its randomly colliding molecules giving up their kinetic energy to free outer orbit electrons. However, the plasma which is produced is then at an undesirably high temperature. In most gases at low temperatures and at moderate pressures, there always exists a small number of free electrons. In air at room pressure and temperature, this electron concentration is about 300 electrons per cubic centimeter. A possibility for ionization is then present in that these few electrons may readily be given enough energy to ionize a neutral gas molecule upon collision. The electrons resulting from initial collision ionization would then collide with more neutral molecules and produce more free electrons, etc. The plasma generated by such collisions would have a low macroscopic temperature because the large positive ions would have slow velocities even though the electron temperature may be in the thousand degree range.

Coupling the free electrons with an energy source is a basic problem which warrants considerable attention. Initially, consider a gas between two electrodes between which there exists a potential gradient. The few free electrons present are accelerated toward the anode by the potential gradient and continue to gain energy until collisions occur between the free electrons and nearby gas molecules. If a free electron possesses enough energy, the collision may produce a positive ion and a slow moving electron (ion pair). The slow moving electron is then accelerated by the potential gradient and may produce another free electron by collision. If the initial free electron does not have enough energy to free an outer orbit electron upon collision with a neutral gas molecule, it may excite the outer orbital electron to an extent that an ion pair may be produced by a

collision between the excited molecule and another slow moving electron. The maximum energy that can be transferred to the free electrons between collisions is a function of the mean free path of the electrons in the gas and the magnitude of the applied potential gradient. For a given gas pressure and temperature, which fixes the mean free path for that case, the energy transfer from a constant unidirectional potential gradient to a free electron is relatively well fixed. Another variable which requires consideration is the possibility of alternating the potential gradient (electric field) direction. To investigate theoretically the influence of an alternating electric field on ion production, the Boltzmann integro-differential equation will be used.

Boltzmann's integro-differential equation is basically a particle-velocity continuity equation written for an element in phase space. That is, a space which not only has three position coordinates but also has three velocity coordinates. It is possible to speak of a six dimensional element in phase space, but the discussion of Boltzmann's equation is often more meaningful if two three dimensional elements, one in coordinate space and one in velocity space, are considered rather than the single six dimensional element in phase space. The three dimensional element in coordinate space has sides dx, dy, and dz, while the three dimensional element in velocity space has sides $d\mathcal{U}$, $d\mathcal{V}$, and $d\mathcal{W}$. The particle influx, or efflux, to the phase space element consists of the particles which move into or out of the three dimensional coordinate space element and at the same time have velocities which lie in the three dimensional velocity space element. Particles which are in the coordinate space element and move into or out of the velocity space element, as a result of collisions, may be

considered mathematically as particles created or destroyed as far as Boltzmann's equation is concerned.

If $\bar{r}$ is a position vector, then Boltzmann's equation which results from the analysis just described may be written as[1]

$$(1) \quad \frac{\partial f}{\partial t} + \bar{\nabla}_r \cdot \bar{\gamma} + \bar{\nabla}_v \cdot \bar{g} = B(t)$$

where $f(\bar{r},\bar{w})$ is a velocity distribution fucrion, $\bar{\gamma}$ is the particle flux in coordinate space of particles having velocities between $\bar{W}$ and $\bar{W} + d\bar{W}$, $\bar{g}$ is the particle flux in velocity space, $B(t)$ is the term resulting from collisions, and $\bar{\nabla}_r$ and $\bar{\nabla}_v$ are the gradient operators in coordinate and velocity space respectively. It may be noted that $\bar{g}$ is a function of the applied electromagnetic forces. When a varying electric field $\bar{E}=\bar{E}p \exp(j\omega t)$ is applied to an ionized gas, a differential equation involving $f(\bar{r},\bar{w})$ of the free electrons may be developed from equation (1) as[2]

$$(2) \quad \frac{\partial f}{\partial t} = B(t) - \bar{\nabla}_r \cdot \bar{w} f + \bar{\nabla}_v \cdot \frac{e\bar{E}f}{m}$$

To solve equation (2), it is necessary to expand f in spherical harmonics (Legendre polynomials) in velocity space and in Fourier series in time.

$$(3) \quad f = \sum_{\ell} \sum_{K} f_K^{\ell}(\bar{r},\bar{w}) P_{\ell} \exp(jK\omega t)$$

Now, if in a given physical situation the mean free path is less than any dimension of the plasma generating space (space between electrodes), if the average motion of the free electrons resulting from the field oscillation

and collisions is sufficiently small so that the applied field does not move the electrons out of the plasma generating space, and if the frequency is high enough so that the electrons do not lose a significant amount of energy between field cycles, then all terms may be dropped from the expansion except the three stated below.[2]

$$(4) \quad f = f_0^\circ + \bar{w} \cdot \left[\bar{f}_0' + \bar{f}_1' \exp(j\omega t) \right] / w$$

That is, the series converges sufficiently fast so that the first three terms will suffice. A preliminary consideration of (4) would be to assume that f_0° is the Maxwellian velocity distribution. However, this assumption is probably not a good one since Maxwell's distribution function does not consider the presence of an electric field.

In equation (1) perhaps the most difficult term to accurately evaluate is B(t), the collision term. As is suggested by Allis[1], let ν_m represent the frequency of collisions which result in momentum transfer only, ν_x represent the frequency of collisions which result in excitation, and ν_i represent the frequency of collisions which result in ionization. Collisions resulting in excitation or ionization differ greatly from collisions producing recoil, scattering, and vibration in that the colliding electron loses most of its energy. Ionization collisions may then be treated mathematically as if fast moving electrons were disappearing from the velocity range between $\bar{w}$ and $\bar{w} + d\bar{w}$ at the rate

$$(5) \quad (\nu_x + \nu_i) f_0^\circ$$

and slow moving electrons in another velocity range were appearing at the rate

$$(6) \qquad q f_o^o$$

By substituting equation (4) into equation (1), making use of the ideas stated above, and equating coefficients of similar time and angle functions, two vector equations and one scalar equation result.[2]

$$(7) \qquad (\nu_x + \nu_i - q) f_o^o = -\frac{W}{3} \bar{\nabla}_r \cdot f_o^1 + \frac{1}{W^2}\frac{\partial}{\partial W}\left[\frac{eW^2}{6m}(\bar{E}_p \cdot \bar{f}_1^1) + \frac{m}{M}\nu_m W^3 f_o^o\right]$$

$$(8) \qquad \nu_m \bar{f}_o^1 = -W \bar{\nabla}_r X \bar{f}_o^o$$

$$(9) \qquad (\nu_m + j\omega)\bar{f}_1^1 = (e\,\bar{E}_p/m)\frac{\partial f_o^o}{\partial W}$$

The components of f_o^1 and f_1^1 may be eliminated from equation (7) by substitution from equations (8) and (9). The result yields a differential equation for f_o^o

$$(10) \qquad (\nu_x + \nu_i - q) f_o^o = \frac{W^2}{3\nu_m}\bar{\nabla}_r^2 f_o^o + \frac{1}{W^2}\frac{\partial}{\partial W}\left[\frac{e\mathcal{U}_c}{3m}\nu_m W^2 \frac{\partial f_o^o}{\partial W} + \frac{m}{M}\nu_m W^2 f_o^o\right]$$

$$\text{where} \quad U_c = eE_p^2 / 2m(\nu_m^2 + \omega^2)$$

The term U_c is seen to have the units of energy (electron volts); in fact, it may be shown that it is the average energy transferred to an electron by the electric field.[2] $\nu_m U_c$ is therefore the power transferred to an electron by the applied alternating electric field. From the expression for U_c, the power transfer is seen to have a maximum at $\nu_m = \omega$. In some respects then, choosing the ω of the applied field as being equal to ν_m is equivalent to matching the impedence of the energy source to the impedence of the load (gas to be ionized) to obtain an optimum condition for power transfer. The problem of optimum frequency is not settled in the physical situation as easily as indicated mathematically, for as ionization occurs in a given case, ν_m does not remain constant. Therefore, an optimized ionization scheme utilizing a alternating electric field would necessarily require that the frequency of the alternating electric field be variable to follow the change in ν_m . Unfortunately, the precise change in ν_m is not altogether obvious.

As an estimate of the electric field frequency requirements to approach an optimum power transfer condition, consider a constant value of ν_m equal to the collision frequency of electrons and molecules in a partially ionized gas. More specifically, consider air at 10 mm of mercury absolute pressure and 70 degrees Fahrenheit that is 25 per cent ionized. For the case stated, ω optimum is approximately 2000 megacycles per second. Physically speaking, this estimate of the electric field requirements indicates that being able to operate with an optimum situation for power transfer is feasible, but not without difficulties. Sources of alternating electric

fields which have a power level sufficient to ionize and which operate at the calculated frequency are not readily available. In addition, given a sufficient electric field source, the handling of this high frequency field is in itself problematic.

FLOW PRODUCTION

A second major problem in the design of the proposed plasma facility is the production of plasma flow in the test section. A present solution to the problem is the blow-down system in which an evacuated region is allowed to fill by passing a gas flow through the test section. However, at the proposed pressures, the blow-down scheme suffers from short operating times and non-uniform test section conditions which tend to limit the scope of possible investigations. For instance, most heat transfer investigations require an appreciable length of time to establish equilibrium conditions. Driving the plasma flow at the proposed pressures (1 to 10 mm Hg absolute) imposes unreasonable requirements on a blower or high volume vacuum pump if high velocities are sought. At low velocities, however, a blower or pump could possibly be used as a workable flow-driving device. For the high velocity range, a more feasible scheme of producing flow has been recently undergoing study. This method involves ionizing the gas to be driven and accelerating it with electromagnetic forces similar to the operation of an electric motor. Basically, this scheme is nothing more complicated than ionizing the gas to be driven with an electric arc (electric field) and placing a magnetic field perpendicular to the electric field. The resulting force on the charged particles which is proportional to $\bar{J} \times \bar{B}$ is in the direction perpendicular to the two fields, a direction which can be conven-

iently used as the flow direction. Published reports of work done in this area of plasma accelerator design[3] indicate that the scheme is workable and high velocities (500 meters per second) may be readily obtained.

The energy transmission from the applied magnetic and electric fields to the flowing gas is essentially that of the accelerated charged particles imparting their kinetic energy to neutral gas molecules by the process of collision. An exact solution to the theoretical problem of determining the velocities produced by given applied fields and test conditions is not readily realizable. However, it is of some interest to discuss a simplified solution for a particular accelerator configuration and compare the theoretical velocity for this situation with experimental data.

Consider the accelerator configuration shown in plate I. In the presence of a constant magnetic field, a stable arc between the two electrodes will generally assume the position shown. While not strictly localized, the arc does tend to be rather well defined, so as an approximation the dotted line shown in plate I will be taken as the line of action of the arc. In this analysis only the electron flow will be considered and not the positive ion flow since the positive ions are relatively large and will not attain comparable high velocities. The component of force in the flow direction acting on an electron in the arc is equal to $\bar{J} \times \bar{B}$. Considering that the electron may be accelerated for the complete mean free path length λ , then the maximum component of velocity obtainable in the flow direction (V_e) is equal to

$$(11) \quad V_e = \sqrt{\frac{2 \bar{J} \times \bar{B} \lambda}{m}}$$

where m is the mass of an electron. If a wall were temporarily placed normal to the flow direction, the pressure excess P_e due to electron bombardment (supposing for an instant that all the kinetic energy of the electrons in the flow direction finds its way to the wall) is given by

$$P_e = \frac{1}{3} n m (v_e)^2 \tag{12}$$

where v_e is an average electron velocity (normal to the surface) and n represents the number of electrons per unit volume. The pressure range being considered (1 to 10 mm Hg absolute) is not excessively low so that the continuum theory may still be used. However, the use of the continuum theory for this case does make the result more approximate. Considering the continuum theory, the Navier-Stokes equation describing the behavior of a Newtonian fluid may be written as[6]

$$\rho \frac{D\bar{W}}{Dt} = \bar{F} - \bar{\nabla} p + \mu \nabla^2 \bar{W} + \frac{1}{3}\mu \bar{\nabla}(\bar{\nabla}\cdot\bar{W}) \tag{13}$$

The component of equation (13) in the x direction (here taken as the flow direction) is

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = F_x - \frac{\partial p}{\partial x} + \mu \nabla^2 u + \frac{\mu}{3}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial v}{\partial y \partial x} + \frac{\partial^2 w}{\partial z \partial x}\right) \tag{14}$$

By the geometry of the physical situation being considered, equation (14) reduces to

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\frac{\partial^2 u}{\partial y^2} \tag{15}$$

The steady state solution of (15) is

$$(16) \qquad u = \frac{1}{2\mu} \frac{\partial P}{\partial x}\left(\frac{b^2}{4} - y^2\right)$$

where b is the radius of the duct. If L is the total length of the duct, then an approximation for $\frac{\partial P}{\partial x}$ is

$$(17) \qquad \frac{P_e}{L} = \frac{1}{3} \frac{nm(\overline{v_e})^2}{L} \cong \frac{\partial P}{\partial x}$$

Combining equations (11), (12), and (17) (for the case $\bar{J}$ perpendicular to $\bar{B}$)

$$(18) \qquad u_{max} = \frac{nJB\lambda b^2}{12\mu L}$$

As has been previously stated, equation (18) has resulted from several approximations and simplifications; however, it does give some insight to the particular physical situation considered. The accelerator configuration shown in plate I is not optimized in that only constant electric and magnetic fields are used. Eckert and Weirick[4] indicate that an optimized plasma acceleration channel requires tailoring the applied fields.

EXPERIMENTAL WORK

To provide some means of verifying the theory previously set forth in this paper and to investigate some problems which are not readily approachable analytically (i.e. electrode geometry), a small prototype plasma wind tunnel utilizing air as the working gas was constructed.

The tunnel itself was a closed loop of 3½" pipe with an upper straight section of cast acrylic tube as shown in plate II. The lower straight

section of $3\frac{1}{2}$" pipe was used to accomodate connections for the vacuum pump, pressure gages, and air bleed (see plate VI). The $3\frac{1}{2}$" screw-on pipe flanges which were used to join the tunnel sections were modified to accept 6" diameter rubber "O" rings for gaskets. The scheme for attaching the acrylic tubing to the system also utlized a 6" "O" ring as shown in plate III. To expediate construction and to compensate for unpredictable tolerance buildups, no acrylic parts were bonded permanently and large tolerance fits were permitted. A liberal amount of Apezon "Q" vacuum sealing compound was applied to the joints and a satisfactory seal was obtained. This scheme proved very quick and successful at the pressure ranges investigated.

The electrodes for producing the accelerating arc were constructed as shown in plate IV. The upper electrode was made movable by using "O" ring seals so the interelectrode distance could be readily varied. Both electrodes were provided with water cooling; however, it was found that only the anode was in serious need of cooling during operation. Early investigations disclosed that the acrylic tube was readily eroded by the accelerating arc, so two sections of asbestos were placed downstream of the arc for the later work. It is of interest that the effect of the arc on the acrylic tube was true erosion (possibly a result of electron bombardment) as opposed to heating and melting. Because of the heat generated by the arc over a long period of time, the accelerator runs were limited to short durations. The magnetic field was produced by the two coils shown in plate V. A variable output D. C. motor generator set was used to energize the magnetic field while a 1100 to 1500 v D. C. power supply was used to produce the accelerating arc.

Several configurations of ionizing electrodes were initially investigated. The first attempt utilized a pair of plates parallel to the flow as shown in

plate VI, the distance between which could be varied. The first set of plates was constructed of brass; however, this initial set was not satisfactory in that surface imperfections seemed to create undesirable areas of localized discharge. A second pair of stainless steel plates did not significantly exhibit this trouble. The use of two plates parallel to the flow for ionizing electrodes was later abondoned because the region of ionized gas between the plates tended to be swept downstream by the flow and became concentrated on the downstream edge of the plates. The resulting plasma region was not of sufficient size nor of sufficient uniformity to be useful. The finalized ionizing electrode scheme consisted of two sections of aluminum honeycomb material (plate VII) placed in series with the flow. The flow of gas in the tunnel still displaced the plasma somewhat from the upstream electrode, but the resulting region of plasma was still uniform enough to be useful. An initial observation might be that the sharp edges of the aluminum honeycomb could cause localized discharge or arcing; however, except for a D. C. ionizing voltage and the very low frequencies (under 5000 cycles), this trouble was not significant.

A variety of pieces of equipment was used to investigate the gas ionization problem. Two different D. C. power supplies with three major voltage points were used to generate D. C. plasma. Their respective output voltages were 1500, 6500, and 13000. In all cases, several values of resistance were placed in series with the ionizing electrodes to protect the power supplies and maintain a reasonably stable discharge. A 1500 ohm series resistance seemed to provide the best results with the 1500 volt potential while the discharge obtained with the 6500 and 13000 volt potentials seemingly could not be optimized by the selection of a series resis-

tance or by varying the electrode spacing. The low frequency alternating voltages were produced by a high voltage amplifier which was driven by a low output oscillator. The high frequency (RF) voltages were produced by a 1kw dielectric heating unit in which the plasma itself was essentially part of the oscillator tank circuit. The RMS value of the alternating voltage placed on the ionizing electrodes was approximately 400 volts and was the same for all successful plasma generating schemes.

Of the various measuring instruments that were used, only the ones which are out of the ordinary will be discussed. The magnetic field intensity between the pole faces was determined with a Rawson rotating coil gauss meter and a typical field plot as shown in plate VIII. The point readings recorded on plate VIII represent an average over an area of about one half square inch. For the sake of simplicity, a deflecting vane was used as a velocity indicating device. (See plate VII) If the gas pressure is known, a drag coefficient for the vane is available, and the gas temperature can be estimated. The velocity of the flowing gas may be computed by the following equation[3]

$$(19) \qquad U^2 = 2\,\frac{P_0 W g}{C_D A}\left(\frac{T}{P}\right)\left(\frac{760}{273}\right)\frac{\sin\theta}{\cos\theta}$$

The data derived from this vane arrangement, while self consistent, is not extremely accurate; however, this measurement method was well suited to the purpose of this thesis. Velocity measurements were taken by first photographing the vane with no flow and then photographing the vane with flow. (See plate XI) In general, the photo of the vane with flow was taken about 30 seconds after the flow was initiated. At the end of this

time interval, the oscillations in the pendulum due to the flow initiation had damped out and the angle of vane deflection could be read from the pictures. A two wire Langmuir probe was used to measure the plasma conductivity. The probe circuit is shown in plate VI and a detail of the probe tip is shown in plate IX. The probe circuit was allowed to "float" (i.e. not grounded) to compensate for any voltages that might reside on the RF generated plasma. A typical curve of probe current vs. probe voltage is shown in plate X. According to the theory developed by Langmuir[5], the plasma conductivity for the curve in plate X is 2.48×10^{-4} mho/cm, the electron temperature is 77,800 degrees Kelvin, and the electron concentration is 2.8×10^{11} electrons per cm^3. No probe measurements were made on the D. C. generated plasma because of its non uniformity.

RESULTS AND CONCLUSIONS

The scope of the experimental work done in conjunction with this thesis was rather limited in that the equipment available made possible only point checks between data and theory. However, some information has been gained regarding the design aspects of a plasma wind tunnel.

At the outset, generating the plasma for the wind tunnel test section by using radio frequency electric fields seems to be more satisfactory than using low frequency or D. C. electric fields. Theoretically speaking, the derivation in this thesis concerning plasma generation indicates that an optimum power transfer between the voltage source and the plasma occurs in the radio frequency range. Only limited experimental comparisons were made, but a visual observation of the plasma generated by comparable power inputs disclosed that the radio frequency generated plasma was considerably more

intense than the D. C. generated plasma. In addition, except for the low end of the pressure range (1 to 2 mm Hg), the D. C. generated plasma was not uniform as a result of a tendency toward localized discharges. Above 5 mm Hg pressure, breakdown of the air could not be accomplished with a D. C. power source without also obtaining a rather intense localized discharge in the plasma.

The problem of driving the flow in the plasma tunnel has at least one solution in the use of electromagnetic forces. While only low velocities were obtained in this investigation, published work in this area indicates that high velocities are easily obtainable. Equation (18), while approximate in nature, produces reasonable agreement with experimental velocities, and it may prove useful in estimating accelerator performance. Equation (18) predicts 0.153 meters per second while the deflecting vane measurement of the actual flow at the same conditions indicated 0.197 meters per second.

To produce a completely satisfactory test facility, several aspects of the plasma tunnel described in this investigation will necessarily require alteration. For the sake of simplicity and convenience, the test section should be made easily removable so that the test configuration may be readily variable. The acrylic tubing should be replaced with a more durable and heat resistant material, particularly in the accelerating arc section. An accelerator which will produce high velocities will also heat the gas being driven, so a heat exchanger in the system will be a necessity to maintain a cool plasma in the test section.

For the low velocities studied in this thesis, the honeycomb ionizing electrodes seem entirely satisfactory; however, some high velocity checks should be made before the ionizing electrode design is finalized.

ACKNOWLEDGMENT

The author wishes to express his gratitude to Robert E. Crank for his assistance in the writing of this thesis.

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APPENDIX

EXPLANATION OF PLATE I

Fig. 1. Accelerating arc detail.

PLATE I

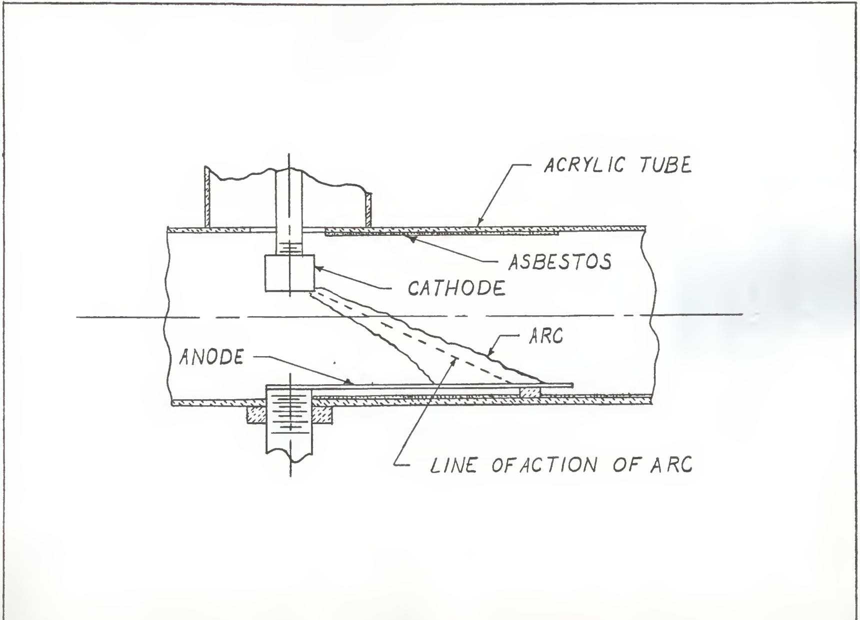

ACRYLIC TUBE
ASBESTOS
CATHODE
ARC
ANODE
LINE OF ACTION OF ARC

Fig. I

EXPLANATION OF PLATE II

Fig. 2. Prototype plasma wind tunnel.

A. Ionizing electrodes

B. Accelerating electrodes

C. Field coils

D. 10 megacycle generator

PLATE II

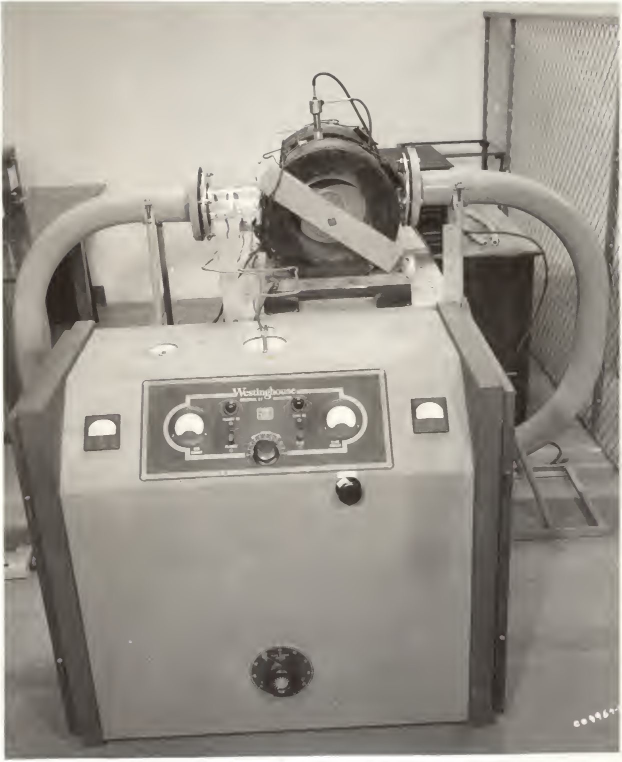


Fig. 2

EXPLANATION OF PLATE III

Fig. 3. Detail of acrylic tube to steel pipe connection.

PLATE III

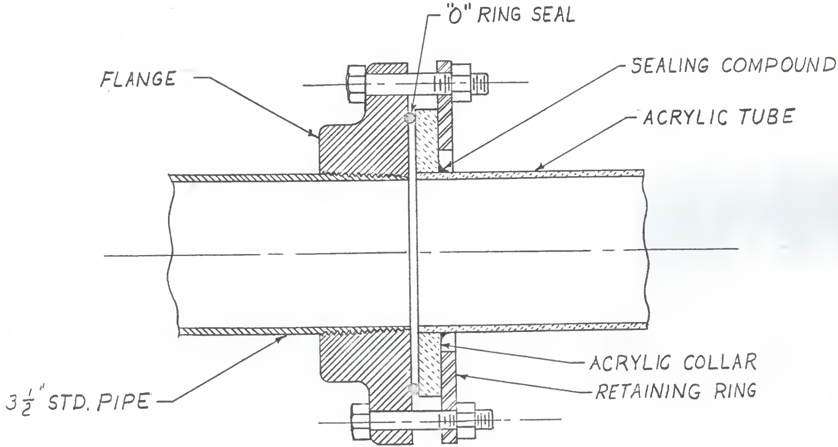


Fig. 3

EXPLANATION OF PLATE IV

Fig. 4. Detail of movable accelerator electrode (cathode). The internal cooling water piping is identical of fig. 5.

Fig. 5. Detail of fixed water cooled electrode (anode).

PLATE IV

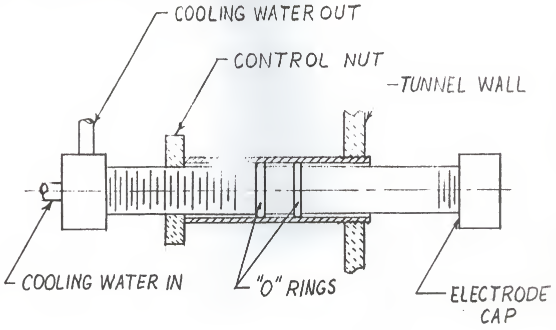


Fig. 4

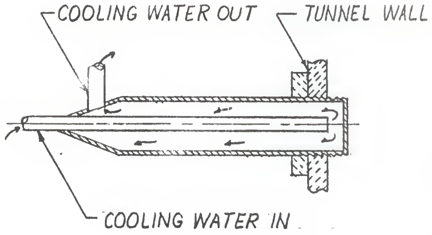


Fig. 5

EXPLANATION OF PLATE V

Fig. 6. Detail of magnetic field coils.

PLATE V

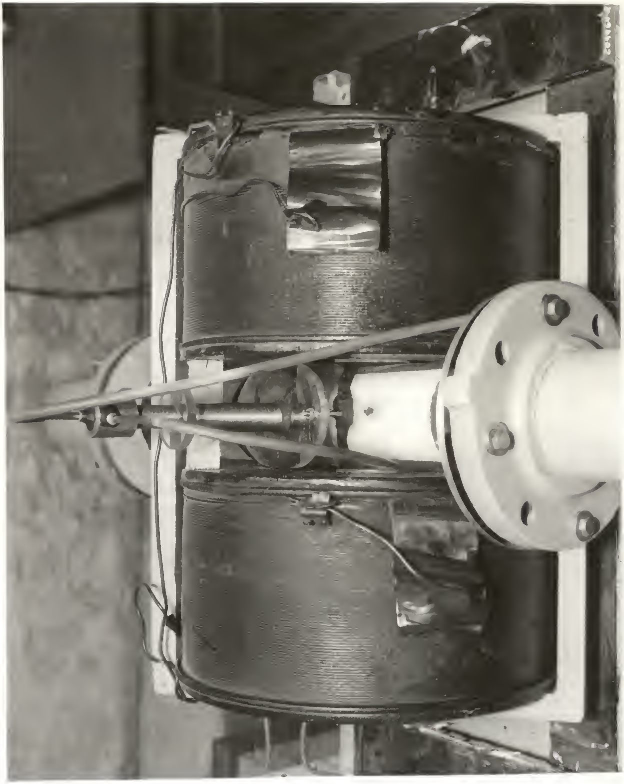
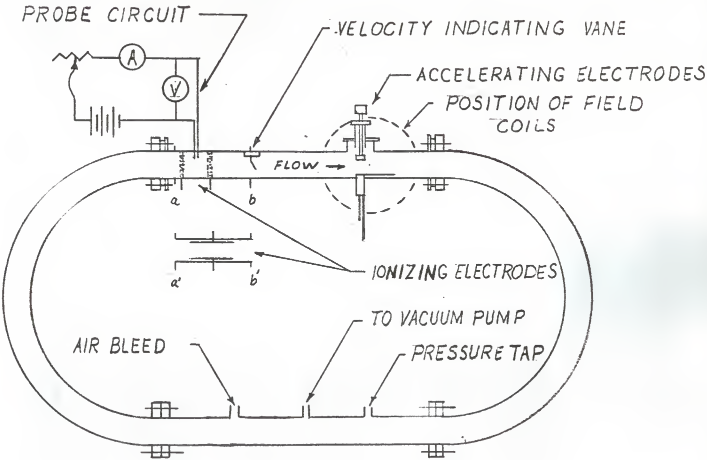


Fig. 6

EXPLANATION OF PLATE VI

Fig. 7. Flow diagram of plasma tunnel.

PLATE VI



NOTE: TWO IONIZING ELECTRODE CONFIGURATIONS ARE SHOWN; THEY ARE NOT USED CONCURRENTLY

Fig. 7

EXPLANATION OF PLATE VII

Fig. 8. Detail of ionizing electrodes and velocity indicating vane.

A. Honeycomb ionizing electrodes

B. Velocity indicating vane

C. Probe

PLATE VII

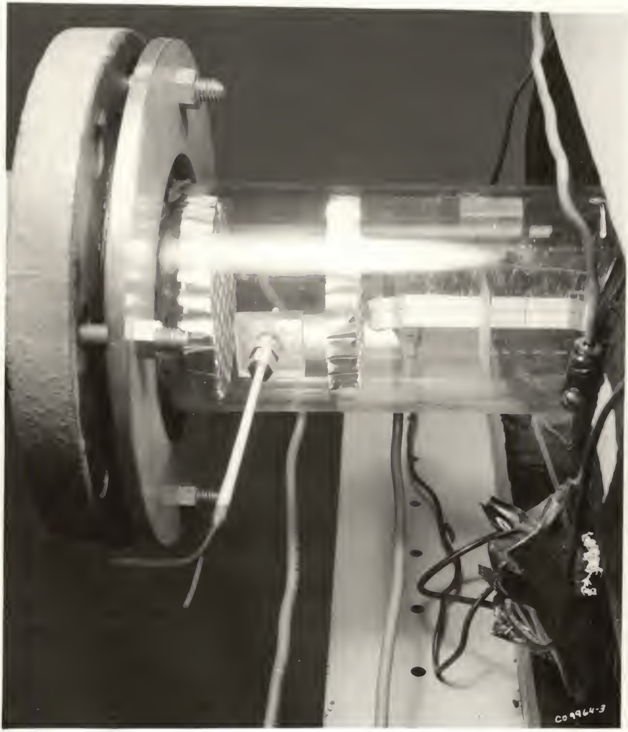


Fig. 8

EXPLANATION OF PLATE VIII

Fig. 9. Magnetic field map.
Current in coils = 28 amp
Readings in kilogauss
Distance between poles = 4 inches

PLATE VIII

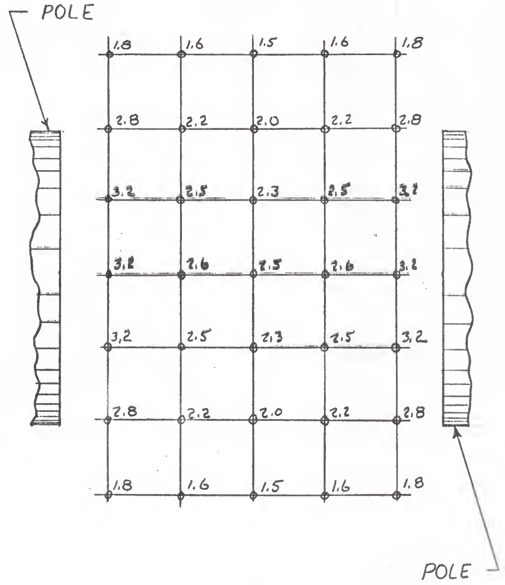


Fig. 9

EXPLANATION OF PLATE IX

Fig. 10. Detail of probe tip. Center to center spacing between tungesten wires = 1 mm.

PLATE IX

Fig. 10

EXPLANATION OF PLATE X

Fig. 11. Plot of probe current vs. probe voltage for 10.7 megacycle ionizing voltage and 0.4 mm Hg absolute pressure. The gas is air.

PLATE X

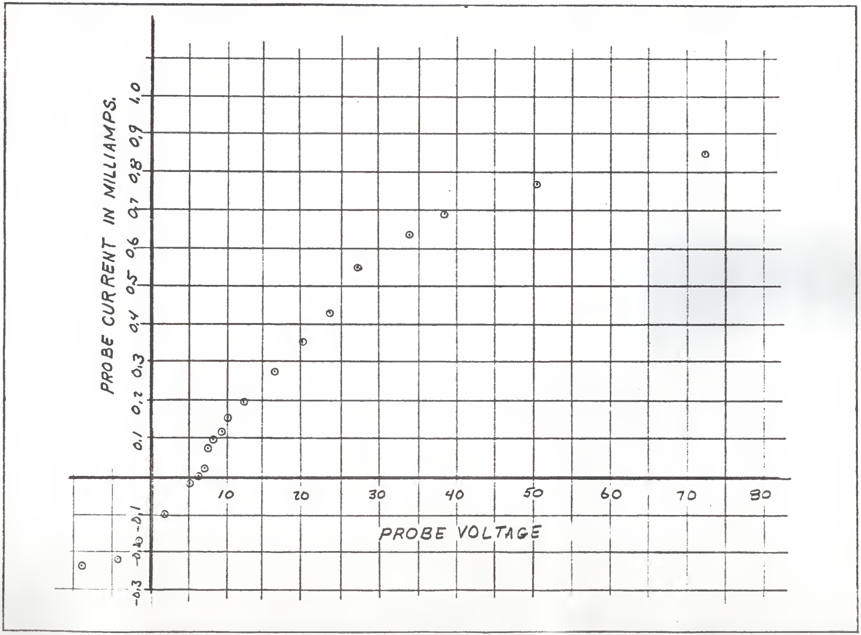


Fig. 11

EXPLANATION OF PLATE XI

Fig. 12. Velocity indicating vane with low flow rate in the system.

Fig. 13. Velocity vane with no flow in the system.

PLATE XI

Fig. 12

Fig. 13

EXPLANATION OF PLATE XII

Fig. 14. Plasma generated by 10.7 megacycle applied field. Pressure $\simeq$ 3 mm Hg

PLATE XII

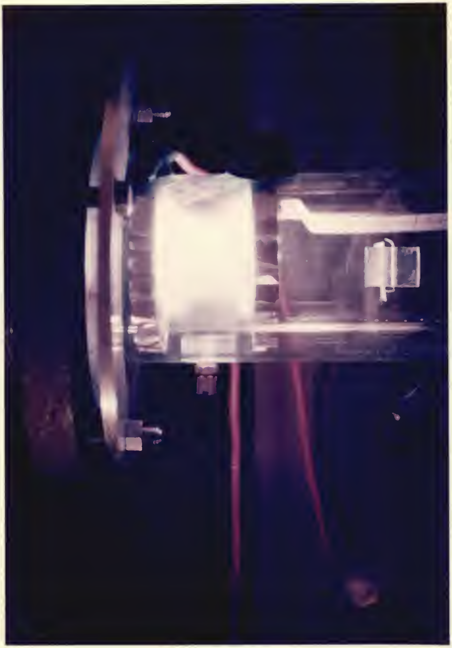


Fig. 14

THE DESIGN ASPECTS OF A LOW TEMPERATURE HIGH PRESSURE PLASMA WIND TUNNEL

by

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AN ABSTRACT OF A

MASTER'S THESIS

submitted in partial fulfillment of the

requirments for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
MANHATTAN, KANSAS

1962

The design of a low temperature high pressure plasma wind tunnel has been studied and a prototype plasma wind tunnel was constructed. Two major problems associated with the design have been investigated analytically and experimentally, and limited correlation was obtained between theory and experiment. The first of the two major problems, that of ionization, was analyzed on a microscopic basis from a consideration of Boltzmann's equation. The analysis indicated that the condition of optimum power transfer between the ionizing field and the plasma occurs in the radio frequency range and more specifically when the field frequency is equal to the frequency of collision between the electrons and neutral gas molecules. This conclusion was partially verified experimentally.

The second major problem considered was the flow driving mechanism necessary to produce plasma flow in the wind tunnel test section. The aspects of using electromagnetic forces to drive the flow were discussed and an approximate relation enabling velocity prediction with a crossed field accelerator to drive the flow was developed. The relation derived produced results which were in general agreement with experimental evidence.

The problem of electrode configuration was considered and a workable design has been tried and proved. Suggestions for improvement of the prototype plasma wind tunnel have been included.